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ELECTRON TEMPERATURES IN THE D REGION

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ELECTRON TEMPERATURES IN THE D REGION

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SUMMARY

Detailed estimates are made of the rates of energy loss of electrons moving in the D region and it is argued that the electron gas has a negligible non-thermal component. The Maxwellian velocity distribution of the thermal component is brought about by collisions with molecular nitrogen involving rotational transitions and the distribution is determined by the neutral particle gas temperature.

INTRODUCTION

It is customary in analyzing radio wave measurements in the D region to assume that the electrons have a Maxwellian velocity distribution characterized by an electron temperature T_e equal to the temperature T_g of the ambient neutral particle atmosphere. Evidence has accumulated in recent years that equality of electron and neutral particle temperatures does not prevail in the upper ionospheric regions [1-5][*] and there have been suggestions that T_e exceeds T_g in the D region also. Thus from observations of cross-modulation, Rumi [6] has derived an electron temperature of $1200^{\circ}K$ at an altitude of 40 km and Belrose and Hewitt [7] have suggested that the collision frequency in the D region is correlated with solar activity, the correlation arising through variations of T_e and not of T_g. A tentative theory has been advanced by Sears [8] which lends support to these observations, but we shall argue the contrary view.

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[*] Numbers in [ ] throughout the text represent reference numbers.

ENERGY LOSS PROCESSES IN THE D REGION

Fast electrons lose energy rapidly in the D region by exciting and
ionizing the atmospheric constituents until their energy falls to about
5 eV. Below 5 eV energy is lost mainly in vibrational and rotational exci-
tation of nitrogen and oxygen and in elastic collisions.

The cross section $\sigma(o,v|E)$ for vibrational excitation of nitrogen by
electrons of energy E

$$e + N_2(0) \rightarrow e + N_2(v) \qquad (1)$$

have been measured by Schulz [9] and Chen [10] has presented a theory which
closely reproduces the measurements. The associated rate of energy loss for
unit density of molecular nitrogen is

$$\frac{dE}{dt} = \left(\frac{2E}{m}\right)^{\frac{1}{2}} \sum_v \Delta(o,v) \; \sigma\,(o,v|E) \qquad (2)$$

where $\Delta(o,v)$ is the internal energy change occurring in the process. The
rate of energy loss through vibrational excitation of N_2 is shown in Figure 1
as a function of impact energy.

There is considerable uncertainty about the cross sections for vibra-
tional excitation of molecular oxygen. Schulz and Dowell [11] have measured
a cross section at an energy of 0.3 eV of about $10^{-18} cm^2$ which is an order
of magnitude smaller than that derived by Phelps [12] from an analysis of
swarm data. The cross sections derived by Phelps are consistent with the
energy loss rates in oxygen, shown in Figure 1. There is also considerable
uncertainty about the cross sections for the excitation of the low lying
electronic levels of molecular oxygen and we shall suppose that the oxygen
curve of Figure 1 includes also the contributions from electronic excitation
processes.

To calculate the rate of energy loss associated with rotational transi-
tions in molecular nitrogen

$$e + N_2(j) \rightarrow e + N_2(j'), \qquad (3)$$
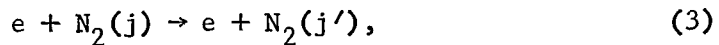
we have employed the cross sections $\sigma(j,j'|E)$ computed by Dalgarno and
Moffett [13] who used the Born approximation and took into account the quad-
rupole interaction [14] and the polarization interaction. Using the dis-
torted wave approximation [cf. 15], attempts have been made to include the
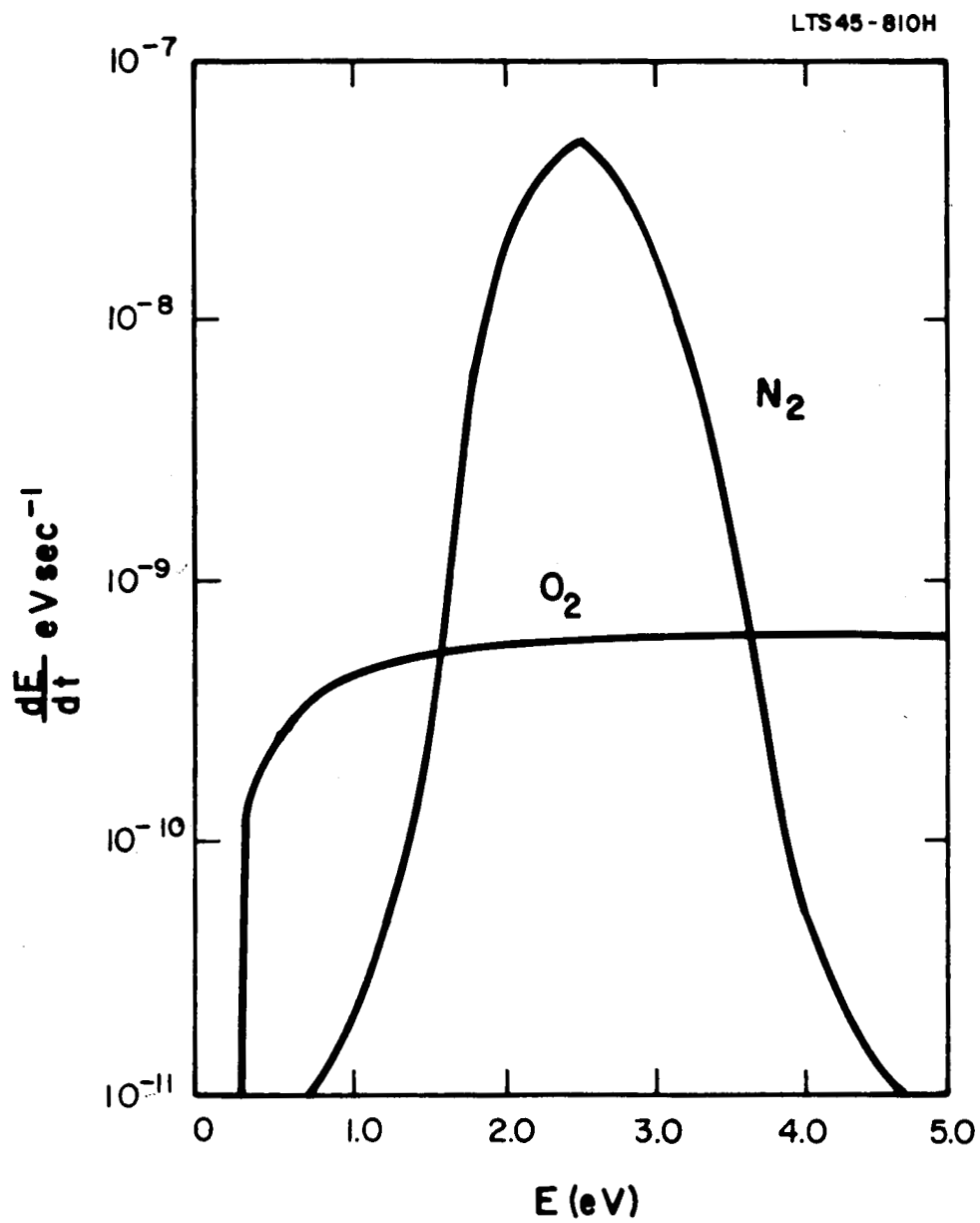
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Figure 1.   Rates of energy loss through vibrational excitation of nitrogen and oxygen.

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distorting effects of the long-range polarization [16-18] but there remains considerable arbitrariness in the final results. The calculations of Dalgarno and Moffett are in reasonable harmony with the analysis of swarm data by Engelhardt, Phelps and Risk [19].

The rate of energy loss for unit density of nitrogen at a temperature Tg is given by

$$\frac{dE}{dt} = \left(\frac{2E}{m}\right)^{\frac{1}{2}} \frac{\sum_{j}\sum_{j'} \Delta(j,j')\sigma(j,j'|E)(2j+1)\exp[-Bj(j+1)/kTg]}{\sum_{j}(2j+1)\exp[-Bj(j+1)/kTg]} \tag{4}$$

where B is the rotational constant. Values of (4) are given in Figure 2 for Tg = 200°K.

We have carried out similar calculations for molecular oxygen, using the quadrupole moment and polarization anisotropy measured by Bridge and Buckingham [20] and the values of dE/dt for electrons in molecular oxygen are also presented in Figure 2.

Energy can be lost in elastic collisions, the energy loss rate being

$$\frac{dE}{dt} = -2\frac{m}{M}\left(\frac{2E}{m}\right)^{\frac{1}{2}} V\, Q_m\left(E - \frac{4}{3}Eg\right) \tag{5}$$

where Eg is the thermal energy of the gas, M is the mass of the molecule and Q_m is the momentum transfer cross section. For nitrogen accurate values of Q_m have been derived by Engelhardt, Phelps and Risk [19] and for oxygen less accurate values have been suggested by Phelps [12]. It follows from them that energy loss in elastic collisions with molecules is negligible compared to loss through rotational transitions.

In the upper ionospheric regions energy loss in elastic collisions with the ambient electrons is an important mechanism for preferentially heating the ambient electron gas and maintaining Te above Tg [21,22]. If n_e cm^{-3} is the ambient electron density, the rate of energy loss by elastic electron-electron collisions is given approximately by

$$\frac{dE}{dt} = -\frac{7.7 \times 10^{-6}}{E^{\frac{1}{2}}}\, n_e\, \ell n(\Lambda eV\ sec^{-1}), \tag{6}$$
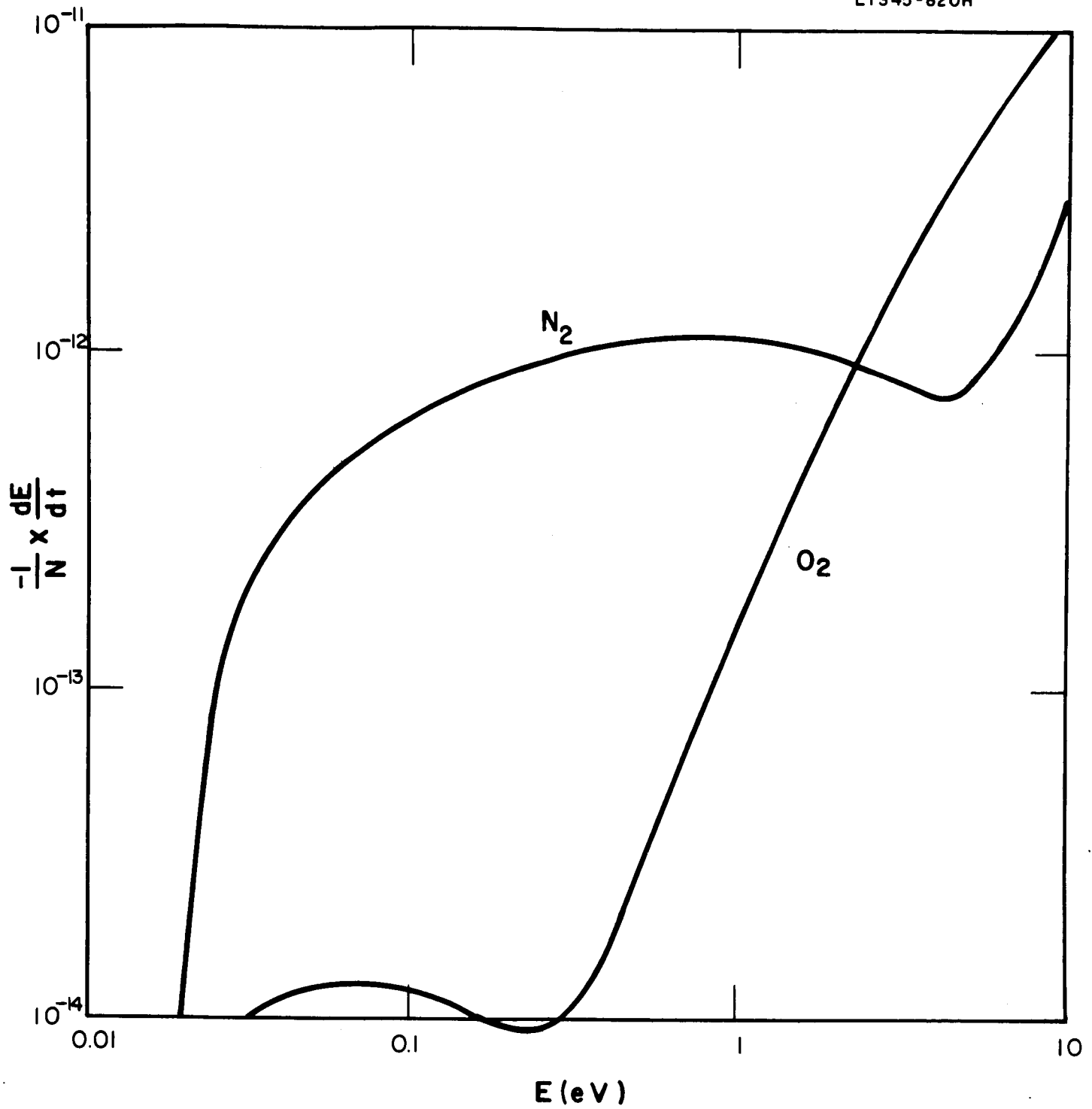
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Figure 2. Rates of energy loss through rotational excitation of nitrogen and oxygen.

where Λ depends upon n_e and Te and E is measured in eV [22,23]. Values of $\ell n \Lambda$ for various electron temperatures and densities are given in Table 1. The electron density in the D region rarely approaches 10^5cm^{-3} even during periods of severe disturbance and an effective upper bound to (6) is accordingly

$$\left| \frac{dE}{dt} \right| < \frac{11}{E^{\frac{1}{2}}} \text{ eV sec}^{-1}. \tag{7}$$

A comparison of (7) with the rate of energy loss from vibrational and rotational excitation of nitrogen and oxygen is given in Figure 3 for electrons moving with energies of 1 eV, 0.1 eV and 0.03 eV in the D region. It is clear that electron-electron interactions are rarely of any importance in the D region. The main mechanisms tending to establish equilibrium consist of rotational transitions in molecular nitrogen so that if the electrons in the D region have a Maxwellian velocity distribution, it will be characterized by the neutral particle gas temperature Tg.

Table 1. Values of $\ln \Lambda$ (Eq. 6)

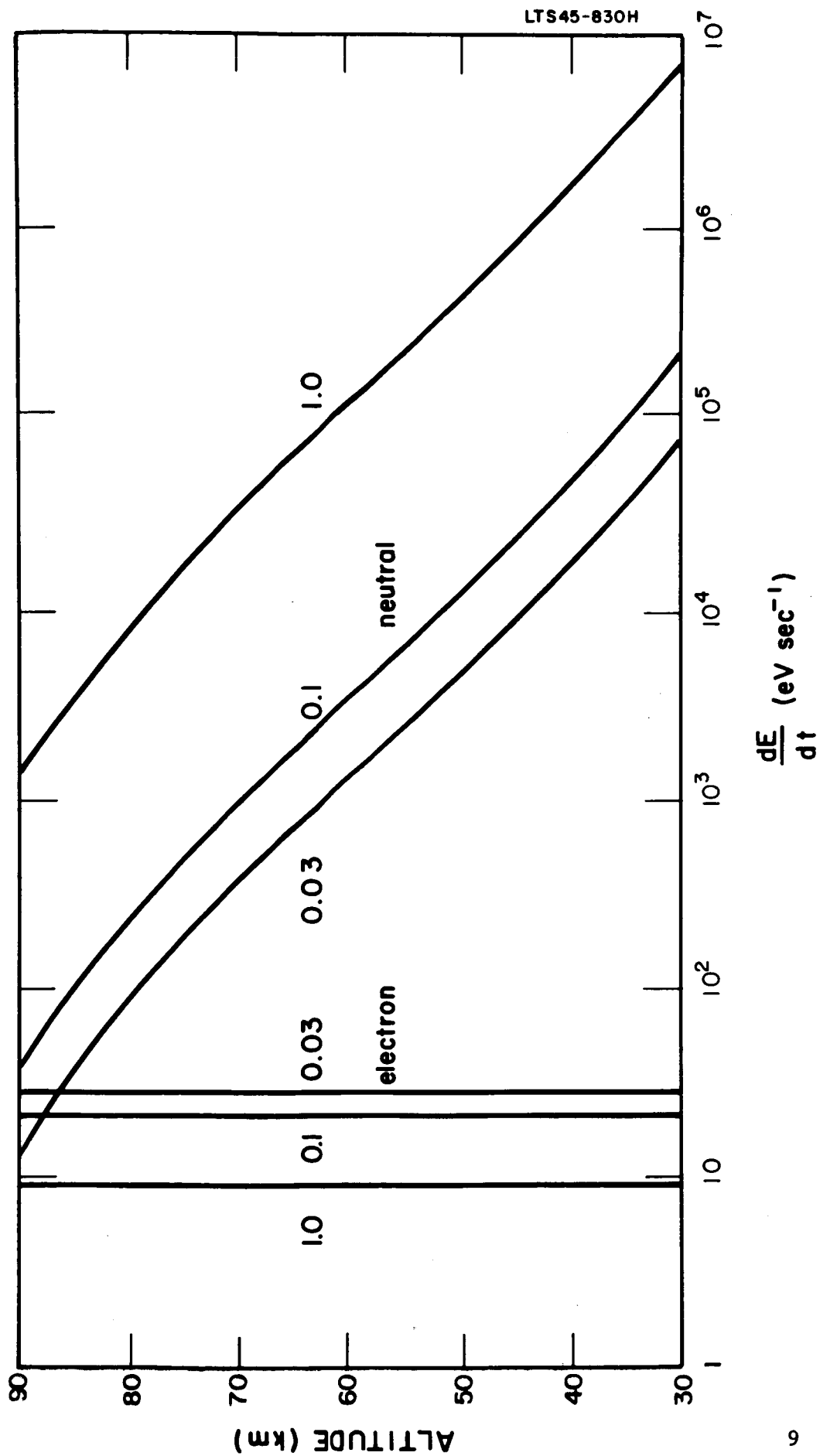| $n_e(cm^{-3})$	10	10^2	10^3	10^4	10^5	10^6	10^7
$Te(^{\circ}K)$							
200	16.2	15.1	13.9	12.8	11.6	10.4	9.3
300	16.8	15.7	14.5	13.4	12.2	11.1	9.9
400	17.3	16.2	14.9	13.9	13.9	12.6	10.3
500	17.6	16.4	15.3	14.1	13.0	11.8	10.7
1000	18.6	17.5	16.3	15.2	14.0	12.9	11.7

Figure 3. Rates of energy loss in collisions with ambient electrons and with neutral particles for incident electrons with energies of 1 eV, 0.1 eV and 0.03 eV.

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PRODUCTION AND LOSS MECHANISMS

The velocity distribution of the D region electrons depends on the electron production and removal mechanisms.* According to a recent review by Reid [24], the normal D region is produced by the absorption of Lyman-α by nitric oxide and by the absorption of X-rays and cosmic rays. During disturbed conditions at middle and low latitudes, the flux of incident X-rays is enhanced, and at high latitudes an additional source of ionization is present, auroral absorption being due primarily to bombarding electrons and polar cap absorption by bombarding solar protons.

The fast electrons produced by the primary ionization processes lose energy rapidly. Some are removed by the two-body dissociative attachment process

$$O_2 + e \rightarrow O^- + O \tag{8}$$

which has a peak cross section of about $1.4 \times 10^{-18} cm^2$ at an energy of about 6.5 eV [25-27], but most are removed by the three-body attachment process

$$O_2 + O_2 + e \rightarrow O_2^- + O_2 , \tag{9}$$
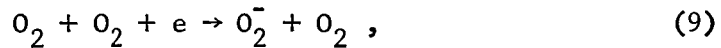
the rate of which has been measured by Chanin, Phelps and Biondi [28].

A comparison of the mean times for energy loss associated with vibrational and rotational transitions and elastic scattering with the mean times for attachment is given in Figure 4 as a function of energy for a neutral particle density of $10^{15} cm^{-3}$ (appropriate to an altitude of 70 km) and in Figures 5, 6 and 7 as a function of altitude for energies of respectively 1 eV, 0.1 eV and 0.03 eV. The energy loss times are in all cases much shorter than the attachment times. Thus nearly all the electrons are converted into thermal electrons before their removal by attachment and the removal mechanism has little effect on the electron velocity distribution. The thermal electrons will have a Maxwellian velocity distribution characterized by the gas temperature T_g. Superimposed upon the thermal distribution there will be a small high energy component, the magnitude of which is enhanced by photodetachment.

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*We are ignoring the effects of electric fields and winds.

Figure 4. Mean times for energy loss associated with (a) vibrational transitions, (b) rotational transitions, (c) elastic scattering, and (d) the mean times for attachment as a function of incident energy at an altitude of 70 km.

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Figure 5. Mean times for energy loss associated with (a) vibrational transitions, (b) rotational transitions, and (c) elastic scattering as a function of altitude for incident energies of 1 eV.
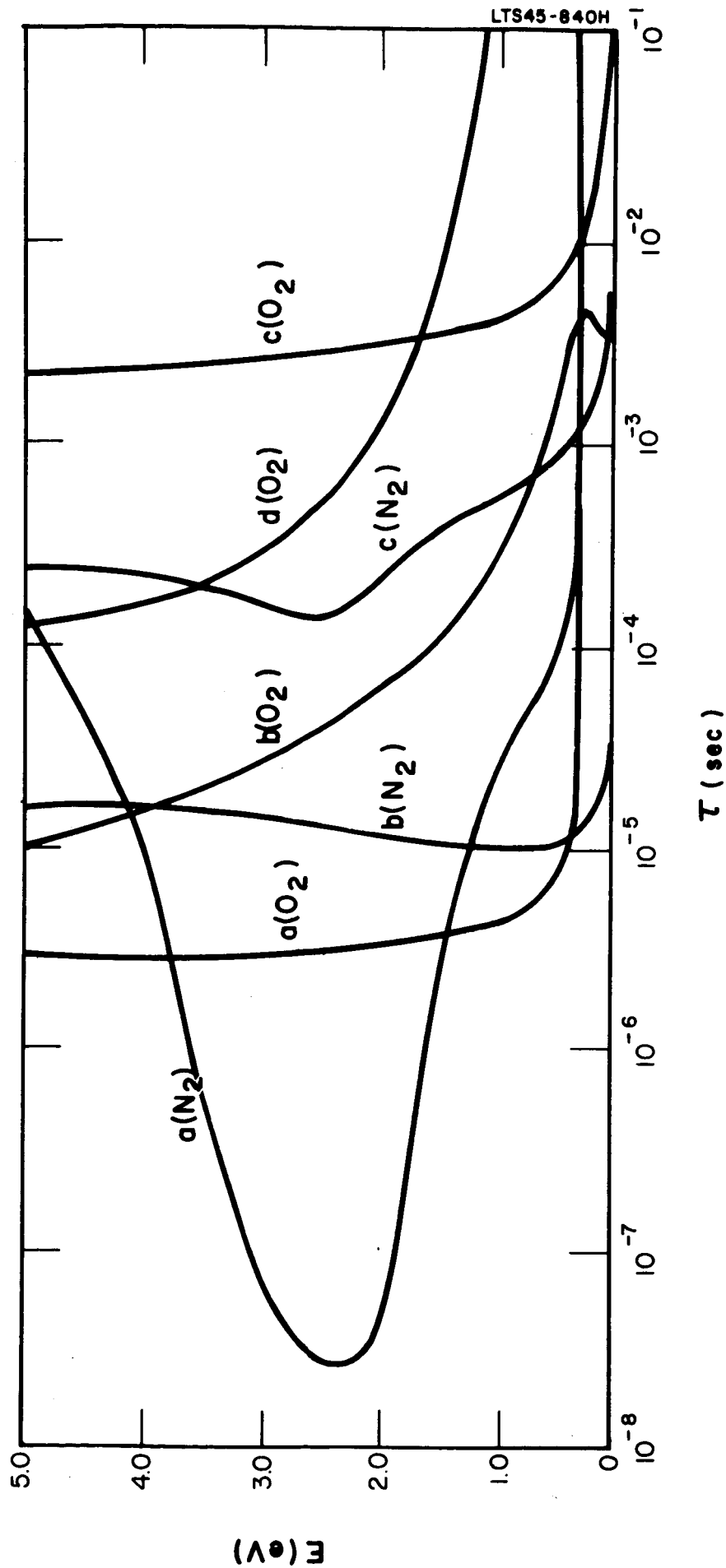
Figure 6. Mean times for energy loss associated with (a) vibrational transitions, (b) rotational transitions, and (c) elastic scattering as a function of altitude for incident energies of 0.1 eV.
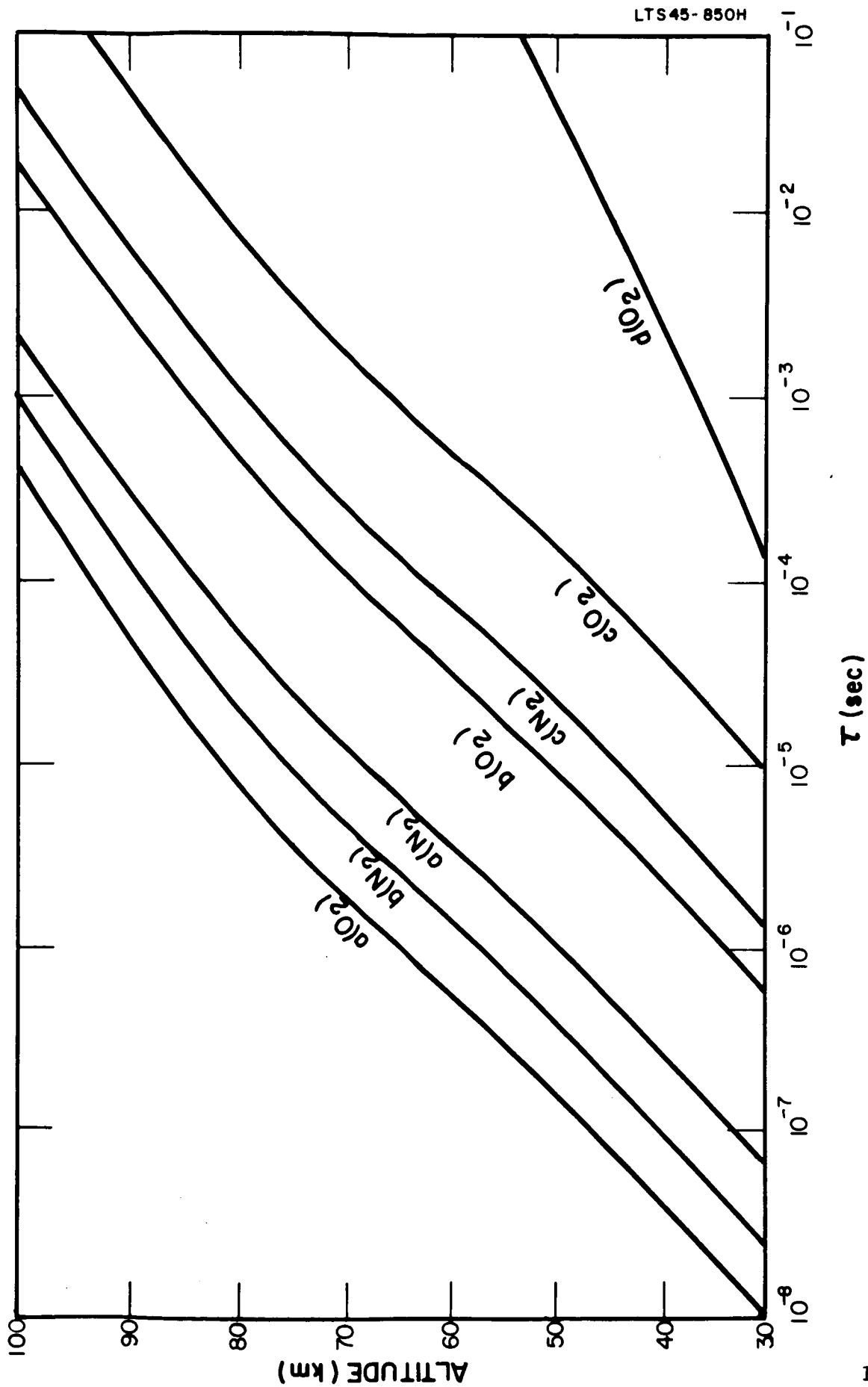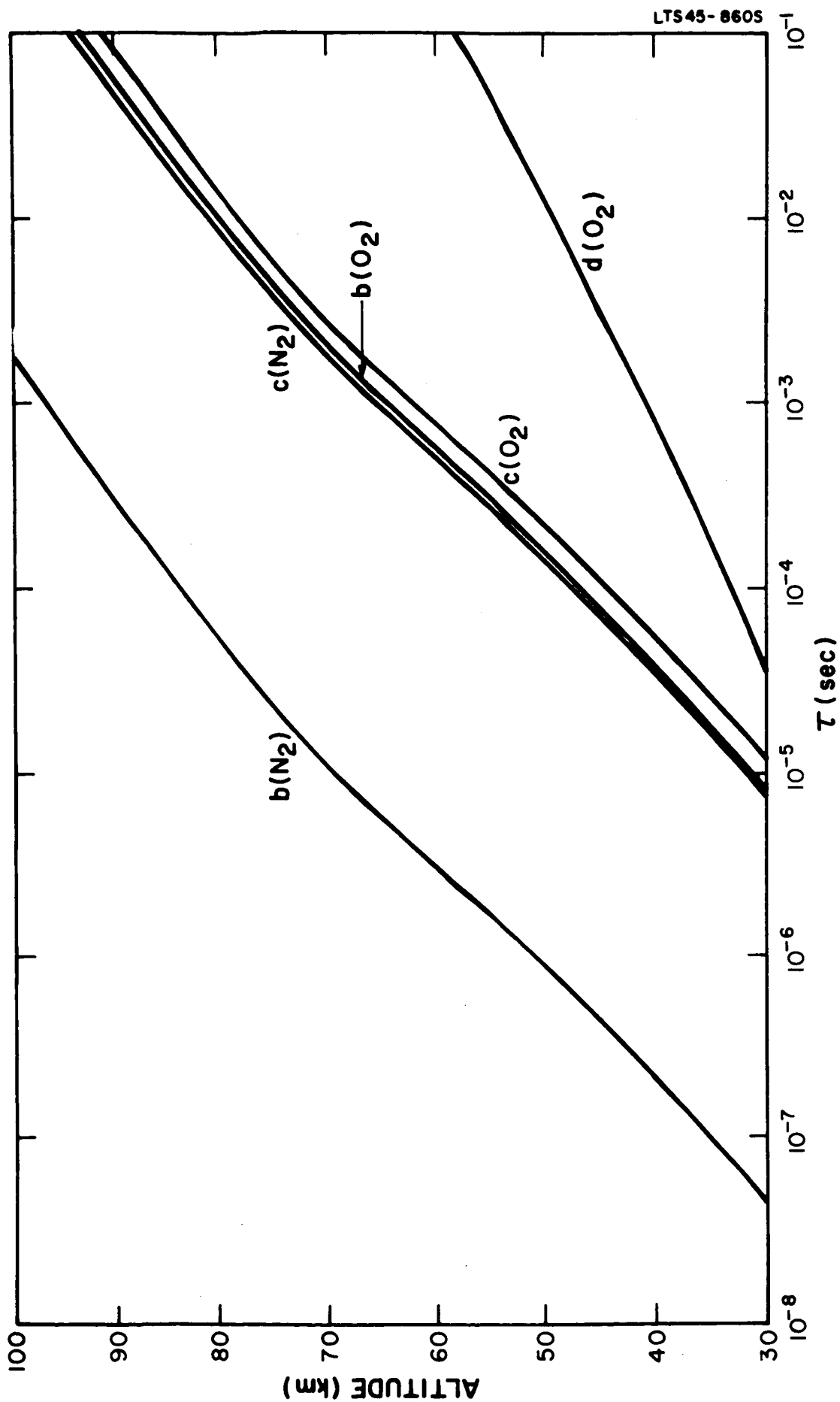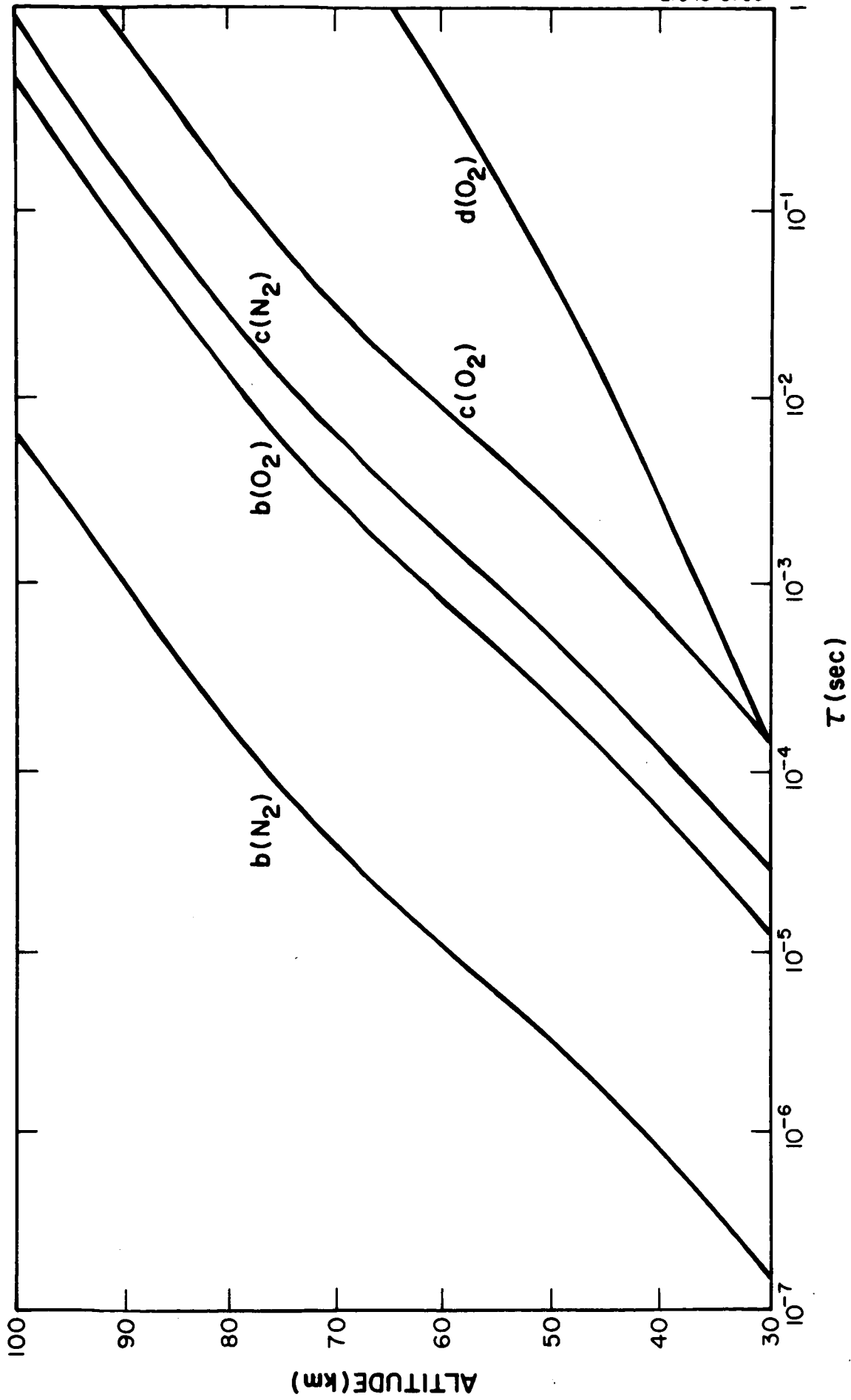
Figure 7. Mean times for energy loss associated with (a) vibrational transitions, (b) rotational transitions, and (c) elastic scattering as a function of altitude for incident energies of 0.03 eV.

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NON-THERMAL ELECTRONS

After an electron attaches to form a negative ion, it is soon detached by the absorption of solar radiation. If the major negative ion is O_2^-, the free electron has an initial energy peaking at about 2 eV. This supply of 2 eV electrons in the daytime D region is much larger than that provided by the primary ionization processes and it may give rise to a substantial non-thermal component in the velocity distribution [8].

An estimate of the non-thermal component of the velocity distribution can be made by equating the number of electrons entering the energy interval dE in unit time to the number leaving it. Then if $f_a(E)$ dE is the number of electrons with energies lying between E and E + dE,

$$f_a(E) = - \sum_{E'>E} q(E') \bigg/ \frac{dE}{dt} \qquad (10)$$

where $q(E')$ is the rate of production of electrons of energy E'.

The shape of the distribution function corresponding to the O_2^- photo-detachment source may be derived from the measured cross sections [cf. 29] and it is shown in Figure 8. The figure demonstrates the efficiency with which electrons with energies between 2 eV and 3 eV are degraded through exciting vibrational levels of nitrogen. In equilibrium, the total number of non-thermal electrons with energies greater than 0.03 eV is approximately

$$n_a = \frac{3 \times 10^{11} \, n(O_2^-)}{N} \quad cm^{-3} \qquad (11)$$

where $n(O_2^-)$ is the number density of O_2^- and N is the number density of neutral particles. The number varies inversely as N because the rate at which an electron loses energy is directly proportional to N. This has the simple consequence that the contribution of the non-thermal component to the collision frequency

$$\upsilon_a = \int f(E) \, \upsilon (E) \, dE/n_e \qquad (12)$$

depends upon altitude through the number density of negative ions only. The actual value of υ_a is given by

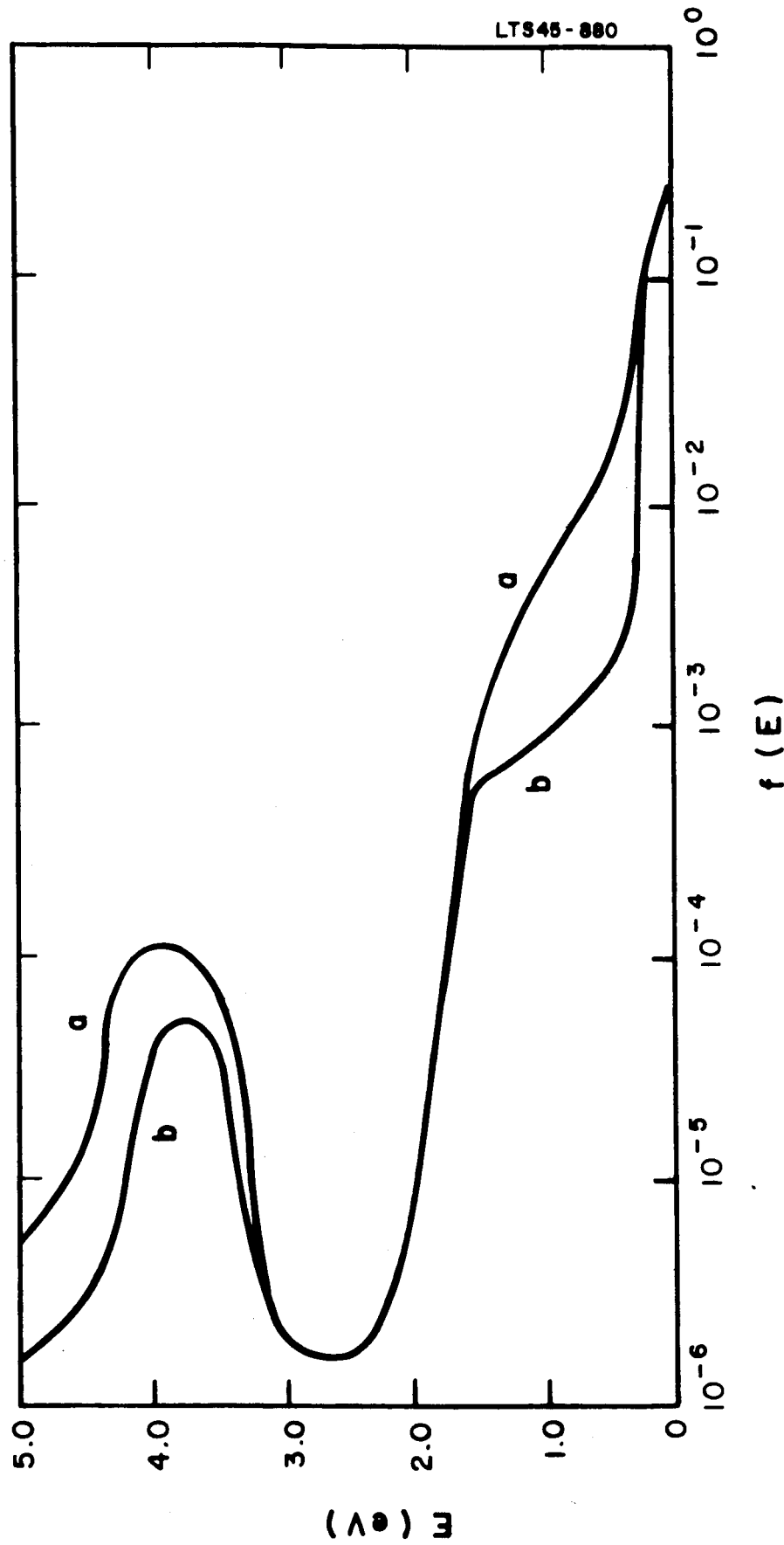$$\upsilon_a = 7 \times 10^3 \, \lambda \, sec^{-1} \qquad (13)$$

Figure 8. The distribution function of the nonthermal electrons ignoring vibrational excitation of oxygen (curve a) and including it (curve b).

LTS45-880

f (E)

E (eV)

where λ is the ratio $n(O_2^-)/n_e$. It is negligible compared to the collision frequency of the thermal electrons. Thus at an altitude of 75 km, $\lambda \sim 1$, $\upsilon_a \sim 7 \times 10^3 sec^{-1}$ and $\upsilon_e \sim 2 \times 10^6 sec^{-1}$ and at 40 km, $\lambda \sim 100$, $\upsilon_a \sim 7 \times 10^5$ sec^{-1} and $\upsilon_e \sim 1 \times 10^8 sec^{-1}$.

The contribution of the non-thermal component to radio wave absorption relative to that of the thermal component is still smaller since absorption of waves of frequency ω is controlled by the expression $n_e \upsilon / (\upsilon^2 + \omega^2)$, which at high energies and at low altitudes reduces to n_e/υ.

Both the thermal and non-thermal components of the velocity distribution will be enhanced during disturbances in the D region. Because fast electrons slow down very rapidly, the shape of the distribution function of the additional non-thermal electrons will be closely similar to that shown in Figure 8. If q $cm^{-3}sec^{-1}$ is the production rate of non-thermal electrons, we find that $n_e \upsilon_a \sim 10^4$ q $cm^{-3}sec^{-1}$.

During a strong auroral absorption event, q may be of the order of 10^4 so that $n_e \upsilon_a \sim 10^8 cm^{-3}sec^{-1}$. With a radio frequency of 30 megacycles per second, an absorption of about 0.001 decibels results from an altitude extent of 10 km, which is negligible compared to the measured absorption of greater than 1 decibel.

The contribution of non-thermal electrons to polar cap absorption similarly is less than 0.1% of the contribution of the thermal component and it appears unlikely that non-thermal electrons are significant in the quiet or disturbed D region.

The correlation between solar activity and collision frequency suggested by Belrose and Hewitt [7] may perhaps be ascribed to variations of atmospheric pressure [30].

Auroral E Region

The velocity distribution of the low energy non-thermal electrons produced during an aurora is similar to that of Figure 8 except that energy loss through excitation of the ^1D level of atomic oxygen causes some depletion of the electrons with energies above 2 eV and elastic collisions with the ambient electrons causes some depletion of the electrons with energies less than 1 eV. We may use our calculations to obtain an estimate of the contribution of non-thermal electrons to radio wave absorption during an aurora.

Visual auroras are classified according to an International Brightness Coefficient IBC θ and in a typical aurora located in the region of 105 km the electron production rate is approximately $10^{3+\theta}$ $cm^{-3}sec^{-1}$ and the equilibrium electron concentration is $3 \times 10^{4+\theta/2}$ cm^{-3} [cf. 31, 32]. The contribution of the non-thermal electrons to the parameter $n_e \upsilon$, which controls

radio wave absorption in the E region, is about $3 \times 10^{7+\theta}$ $cm^{-3}sec^{-1}$ and the contribution of the thermal component is about $10^{9+\theta/2}$. Thus the two contributions become comparable for an aurora of brightness IBC III. The actual absorption is not large but Reid [24] has suggested that for brief periods during bright auroras the non-thermal absorption may be detectable.

COOLING IN THE D REGION

If the electron gas in the D region is heated preferentially so that Te exceeds Tg, it will cool mainly by rotational excitation of molecular nitrogen if T is less than 1300°K and by vibrational excitation of molecular nitrogen if Te exceeds 1300°K. The rate of cooling through rotational excitation may be derived from calculations by Dalgarno and Moffett [33] and by Altshuler [34]. It is given approximately by

$$\frac{d\,Te}{dt} = \frac{-3 \times 10^{-10}\ (Te - Tg)}{Te^{\frac{1}{2}}}\ N\ {}^{\circ}K\ sec^{-1} \qquad (14)$$

where N is the air density. Values of the cooling rate for a gas temperature of 200°K are given in Table 2. The rate of cooling through vibrational excitation may be derived from calculations by Chen [35]. Values of it are given in Table 2.

The electron temperature of 1200°K derived by Rumi [6] at an altitude of 40 km implies, according to Table 2, an energy deposition into the electron gas of the order of 10^7 eV cm^{-3} sec^{-1} for an electron density of 10^2 cm^{-3}. Such an energy deposition rate seems unacceptably large and the interpretation of Rumi's observations through an enhanced electron temperature is implausible.

Table 2. Cooling rates $-\frac{1}{N}\frac{d\,Te}{dt}$ °K/sec-cm^3 for rotational and vibrational excitation

	Electron Temperature, Te, °K					
	200	300	500	1000	1500	2000
Rotational (Tg = 200°K)	0	1×10^{-9}	2×10^{-9}	5×10^{-9}	7×10^{-9}	7×10^{-9}
Vibrational	3×10^{-15}	8×10^{-13}	8×10^{-11}	2×10^{-9}	9×10^{-9}	2×10^{-8}

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